CROMOS: A cryogenic near-infrared, multi-object spectrometer for the VLT

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Abstract. We discuss a cryogenic, multi-object near-infrared spectrometer as a second generation instrument for the VLT. The spectrometer combines 20 to 40 independent integral field units (IFUs), which can be positioned by a cryogenic robot over the entire unvignetted field of the VLT (∼7'). Each IFU consists of a contiguous cluster of 20 to 30 pixels (0.15 to 0.25" per pixel). The individual IFUs have cold fore-optics and couple into the spectrograph with integrated fibers-microlenses. The spectrometer has resolving power of $\lambda/\Delta\lambda \sim 4000$ and simultaneously covers the J-, H-, and K-bands with three HAWAII 2 detectors. The system is designed for operation both in seeing limited and MCAO modes. Its speed is approximately 3500 times greater than that of ISAAC and 60 times greater than NIRMOS (in H-band). The proposed instrument aims at a wide range of science, ranging from studies of galaxies/clusters in the high-z Universe (dynamics and star formation in z>1 galaxies, evolution of ellipticals, properties of distant, obscured far-IR and X-ray sources), to investigations of nearby starbursts, star clusters and properties of young low mass stars and brown dwarfs.

1 Motivation and Science Drivers

Optical photometry/spectroscopy is the easiest and most commonly used technique for studying stellar and interstellar components in galaxies. Yet extinction/reddening by dust and cosmological redshift are two of the reasons that make observations in the near-infrared (NIR: $\lambda \sim 1$–$2.4\ \mu$m) necessary and/or highly attractive. The much better performance of adaptive optics at infrared wavelengths is another. Furthermore the NIR emission traces older stellar populations that are better measures of stellar mass in galaxies, and there are a number of NIR spectral features (e.g. H_2, CH_4, H_2O etc.) that uniquely trace cool interstellar and circumstellar gas. Because of poor detector performance and size, low instrument transmission and high sky brightness, however, infrared observers until a few years ago had to pay a price of >3 mag in sensitivity compared to optical spectroscopy, making NIR spectroscopy of distant or faint sources challenging or impossible (Figure 2). With the advent of new high quality detectors and spectrometers, such as ISAAC on the VLT and NIRSPEC on the Keck telescope [10][11], combined with software suppression of the OH sky emission lines, NIR long-slit spectroscopy has become competitive with optical spectroscopy. Adaptive optics assisted, integral field spectroscopy (e.g. with SINFONI on the VLT [14]) will soon open up sensitive, near-diffraction limited, NIR

imaging spectroscopy. The next obvious steps are NIR multi-object spectroscopy with cryogenic slit masks. Two examples are FLAMINGOS for GEMINI [5] and LUCIFER for the LBT [9]. An additional option is a cryogenic multi-object spectroscopy with independent integral field units. Although it is certainly a challenging endeavor, it is also the most versatile and sensitive option. It is this option that we propose here.

As an example of the wide range of science issues that can be addressed with such an instrument, some of the key science drivers are,

1. dynamics and physical characteristics of z>1 star forming galaxies,
2. evolution of the most massive galaxies, notably ellipticals at z>1
3. redshifts and properties of distant dusty starbursts and faint hard X-ray AGNs,
4. age dating/population studies of starbursts and stellar clusters, and
5. spectroscopy of young low mass stars and brown dwarfs.

Project 1) calls for high quality Hα (and other emission lines) profiles in a large number of galaxies of different characteristics, for studying the cosmological evolution of galaxy mass and studying the cosmological evolution of galaxy mass and mass-to-luminosity ratio. Spatially resolved measurements with $\ll 0.5$" resolution (in good seeing, or with AO) are necessary to resolve rotation curves in sources that are typically 1" to 2" in diameter. Both hierarchical merger scenarios in a cold dark matter Universe and current observations at z<1 and z>2.5 indicate that for 1<z<2 galaxy properties should exhibit rapid evolution, which would be most pronounced for the most massive systems. J/H/K observations are necessary for addressing the Hα line. Another goal is the investigation of metallicities, stellar populations and star formation histories through emission line ratios, where spatially resolved information is desirable but not in all cases necessary (or possible). In conjunction with recent theoretical models, studies of the dynamics and star formation properties of large samples of high-z galaxies, especially in the critical range between z=1 and z=2.5 (reachable only or primarily with infrared observations), will give a better understanding of the processes involved in galaxy formation/evolution and the formation of the Hubble sequence. This project (as well as others on the list) exemplifies the shift in observational cosmology during the next years away from pure redshift studies, and toward detailed spectroscopic investigations of the physical properties of large samples of individual objects.

Project 2) aims at the important issue of how the most massive galaxies evolve, when and how elliptical galaxies were formed, and whether some ellipticals formed very early (z$\geq$3) through major starbursts. It will require high signal-to-noise ratio spectra to get at key absorption lines (Balmer lines, Mg b, G-band, etc.) for redshift determinations, measurements of velocity dispersions, metallicities and ages. Distant ellipticals and dusty star bursts are often extremely red (R$-$K>5) so that only infrared spectroscopy has a chance of getting redshifts and/or information on their physical characteristics.

Project 3) requires determination of emission line redshifts for larger samples of the faint far-infrared/submm sources found by ISO, SCUBA and MAMBO

(and in the future by SIRTF, FIRST/HERSCHEL and ALMA) and of the hard X-ray sources currently discovered by XMM-NEWTON and CHANDRA. The final objective of this project is an investigation of the relationship and relative cosmological evolution of powerful starbursts and accreting massive black holes.

The goal of project 4) is an empirical determination of the temporal and spatial evolution of nearby starbursts for a more detailed understanding of global star formation processes (feedback, superwinds, initial mass function, globular cluster formation, etc.). Apart from being a key issue in its own right, this project also serves as input for the high-z studies mentioned above.

Project 5) aims at a better understanding of the properties and evolution of young (pre-main sequence) low mass stars and brown dwarfs through detailed NIR spectroscopy. These cool objects have characteristic molecular absorption bands in the 1–2.4 μm that can be used, in conjunction with theoretical models, to more quantitatively understand their structure, atmospheres and evolutionary state.

Common to all these projects is that they aim at a physical understanding of faint objects through detailed, spatially resolved spectroscopy at the best possible sensitivity and with a broad wavelength coverage of samples with statistically meaningful sizes.

A critical question is the expected density of sources. Figure 1 summarizes the surface densities of the sources in projects 1–3. For the magnitude limits of a ground-based instrument on the VLT (AB$\sim$21–23, K$\sim$19–21), there are typically between a few to a few tens of sources in the 7' unvignetted field of view of the VLT.

2 Instrument characteristics

To achieve the requirements just mentioned, a suitable multi-object spectrometer has to have the following characteristics:

1. cryogenic operation and OH sky line suppression/avoidance for optimization of sensitivity out to 2.4μm,
2. simultaneous coverage of J-, H-, and K-bands at spectral resolving powers sufficient for high quality dynamical studies and for software OH suppression ($\lambda/\Delta\lambda \geq 4000$),
3. individual integral field units covering typical object sizes ($\geq$2") at pixel scales suitable for spatially resolved studies ($\sim$0.15" to 0.25"), and
4. 20–40 IFUs movable over at least the unvignetted field of view of the VLT at Nasmyth focus.

It is also highly desirable that such an instrument can interface with and work behind wide-field adaptive optics systems (such as multi-conjugate AO: MCAO), in order to image at <0.3" resolution.

The point source sensitivity of our proposed CROMOS fulfilling the above requirements is shown in Figure 2, in comparison to other facilities/instruments and to z$\sim$2 elliptical/starburst galaxies.

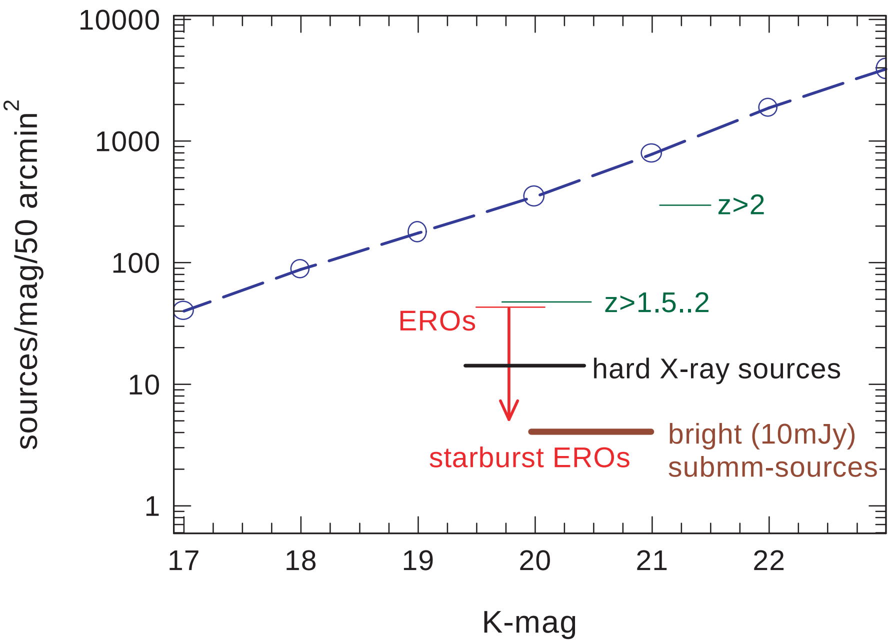

Fig. 1. Source surface densities as a function of K-band magnitude. The dashed curve and circles denotes the K-band source counts [1]. The fractions of those sources at high redshift are denoted by upper bars [6][12]. The source density of 2–10 keV sources ($\geq 2\times10^{-15}$ erg/s/cm^2 [7]) is indicated as a thick bar. The surface density of extremely red objects (EROs: R$-$K>5) is marked by a bar [3], with an arrow denoting the fraction of EROs that are likely dusty starbursts (rather than early-type galaxies). The source density of bright ($S_{850\mu m}\geq$10 mJy) submm sources [2] is indicated by the lowest bar.

3 Key technologies

3.1 Spectrometer layout

The basic layout of the spectrometer and camera derives its design and heritage from that of the SPIFFI spectrometer for the VLT [4]. It consists of pre-optics to re-image the object plane from the AO, an image-slicer to cut the two-dimensional field into a set of slitlets, and a spectrometer with an f/30 collimator and an f/1.4 camera. Another important function of the pre-optics is to suppress the thermal background with the cold stop. The camera is a refractive optics using commercial glasses. The key difference with the SPIFFI design, other than the image slicer, will be the separation of the J-, H- and K-band light in the collimated part of the beam through beam splitters, followed by three independent gratings, cameras and detectors covering these three bands. With three HAWAII 2 detectors and $\lambda/\Delta\lambda\sim$4000 the entire wavelength range from 1μm to 2.4μm can be sampled at the Nyquist rate. The alternative of directly dispersing light onto the detectors with a single grating is very difficult due to

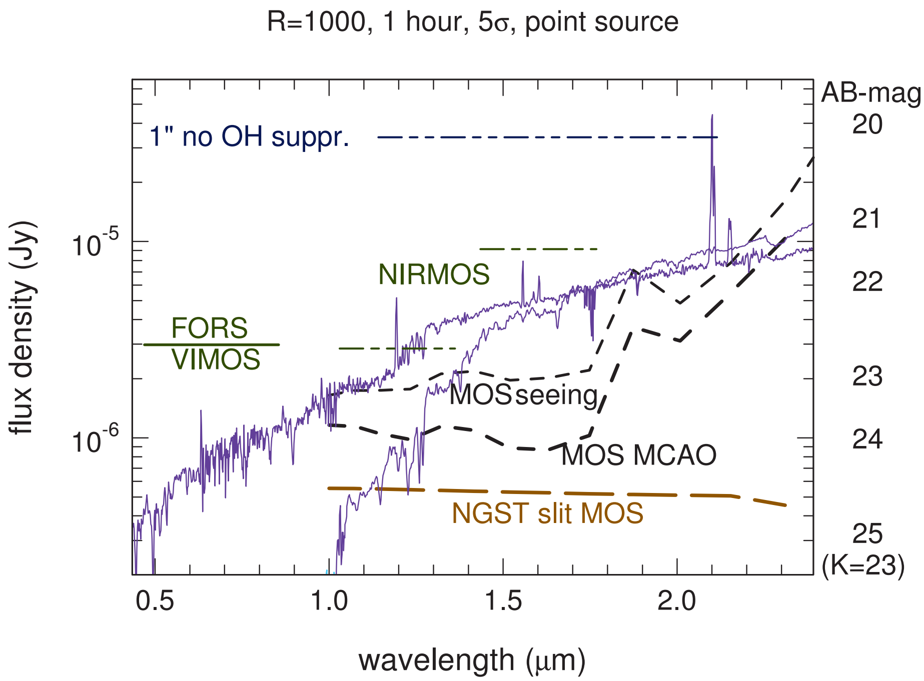

Fig. 2. Point source sensitivity (5σ, 1hour integration time at $\lambda/\Delta\lambda$=1000, upper dashes) of the proposed cryogenic MOS, in comparison to other instruments/facilities. For comparison the spectra of a moderately extincted starburst galaxy (bluer spectrum) and an elliptical galaxy (redder spectrum) are shown, for a redshift of 2.2 and an AB magnitude of 22 [8]. Note the very substantial improvement between OH suppressing/avoiding NIR spectrometers with sub-arcsecond slits (such as ISAAC, NIRSPEC and NIRMOS) compared to instruments without these features (even on an 8m telescope: long-short-short dashed line). NIRMOS (long-short dashed bars) is not cryogenic, however, resulting in non optimum H-band performance (and no K-band capability). Because of its integral field nature, the CROMOS gains another factor of $\sim$2 for compact sources, since the effective 'slit' can be optimized for the shape of the source and the seeing. The lower dashed curve gives the performance of the MOS in conjunction with a high performance (2μm Strehl ratio 0.7) MCAO system and 0.2" (software) pixels. Only the NGST multi-slit MOS (lower long dashes) outperforms the CROMOS, especially at $\lambda\geq 2\mu$m. Between OH sky lines, the point source performance of the CROMOS (in terms of flux density of AB magnitude: AB=$-2.5\log S_\nu$(Jy) + 8.9) is significantly better than that of optical multi object spectrometers, such as FORS or VIMOS. Note, however, that a few percent of the wavelength range covered by the MOS are strongly affected by OH sky lines, and thus must be discarded for faint source spectroscopy.

the challenging camera optics (f/1), the very wide wavelength range, and due to the fact that the HAWAII 2 detectors are non-buttable.

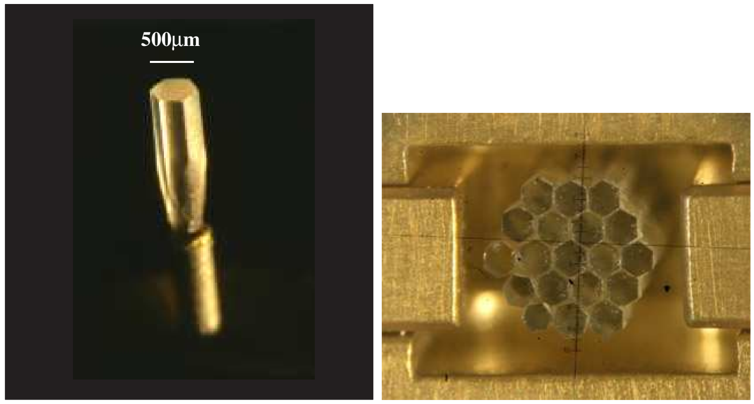

Fig. 3. Flared fiber-integrated microlens technology [13]. The left inset shows a single flared fiber (core diameter 50μm) with its integrated hexagonal microlens. The right inset shows a 19 element fiber IFU that is somewhat similar to the IFUs intended for the CROMOS.

3.2 Integrated flared fiber-microlens IFUs

We have tackled the well known problem of low coupling efficiency through fibers from the telescope into a spectrograph, especially in a cryogenic environment, by developing the 'integrated flared fiber-microlens' technology [13]. This concept uses the polished, flared tip of a silica fiber as an integrated microlens, thus efficiently coupling light from the telescope pupil into the core of the fiber (left inset of Figure 3). The hexagonal surface cut of the tip allows a contiguous areal coverage as required for the IFUs of the MOS discussed here (right side of Figure 3). While Figure 3 shows a hexagonal arrangement of a fiber cluster, other configurations (e.g. reactangular) are possible and may better match the elongated shapes of distant galaxies. With $\sim$15 cm fiber lengths we have achieved throughput of $>$80% at 2 μm from an f/62 input beam to the end of the fiber. The flared fiber-integrated microlens technology minimizes reflection losses and misalignments in the cryogenic environment. Nevertheless we are presently also investigating the performance of such separate microlens-fiber systems. In the CROMOS the lengths of the fibers would have to be $\sim$50 cm, thus reducing the transmission to about 85% at the upper part of the K-band, near an absorption feature of silica, but little affecting the performance at $\leq$2.4 μm. The primary challenge of our flared fiber development up to now was the small tolerances of the micro-machining/polishing, thus leading to poor production yields of high throughput fibers. This issue will have to be dealt with in the next phase of the development.

3.3 Spider arms and cryo-robot

Cold fore-optics are required to efficiently couple the light into a given IFU/fiber cluster and reduce the thermal background. For this purpose and for the mechanical movement of the IFUs across the field of view, we are adopting a 'fishermen-around-the-pond' arrangement of spider arms. Figure 4 shows the mechanical arrangement and optical trains of the spider arms containing the fiber clusters, along with their cold fore-optics. A field lens at the dewar window is required for centering the pupil onto the cold stop wherever the IFU is on the focal plane. Figure 4 shows an example of optical design in the bottom left. The field lens changes the direction of the light into the right angle to the focal plane, which is spherical. The spider arms are fastened with magnets at the back of the spherical, soft iron plate (Figure 4 bottom right).

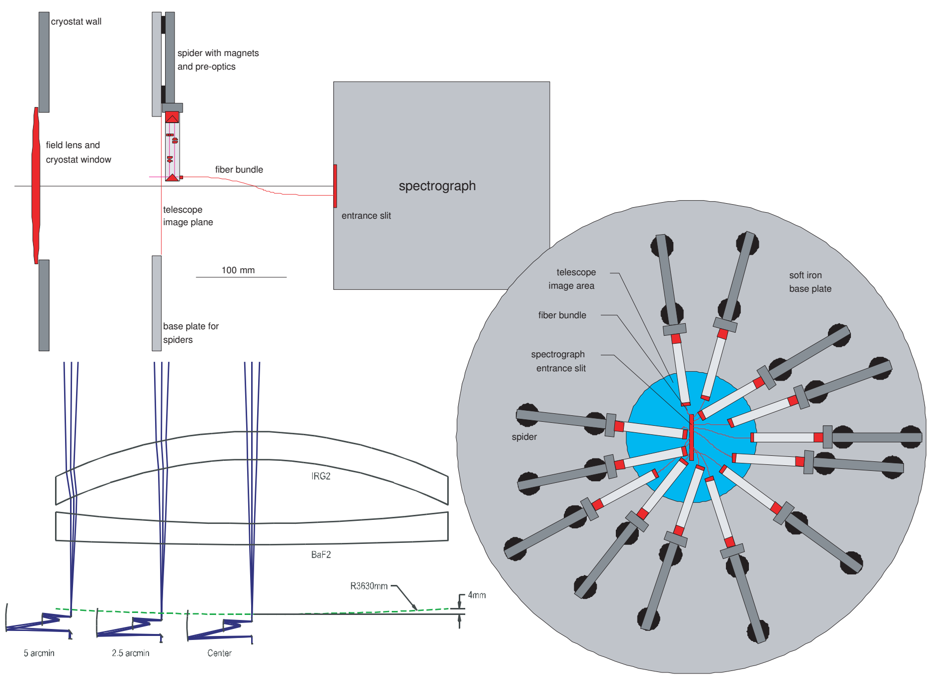

Fig. 4. Optical layout of the CROMOS. Top left: Side view showing field lens, cold fore-optics for one of the spiders mounted on the magnetic plate, coupling its fiber bundle into the spectrograph. Bottom left: Ray tracing through the field lens and fore-optics. Bottom right: Top view showing the 'fishermen-around-the-pond' arrangement of the spiders.

We have developed a cryogenic robot to place the spider arms anywhere in the field of view. The robot (Figure 5) has three degrees of freedom, one full rotation of the entire device and two linear motions along two side of a parallelogram.

The robot is designed to work at LN_2 temperature and should be able to place 20 arms in about 5 to 10 minutes. We have developed the first version of the drive software and have successfully tested the operation of the device at room temperature. Cold tests will follow in the next few months.

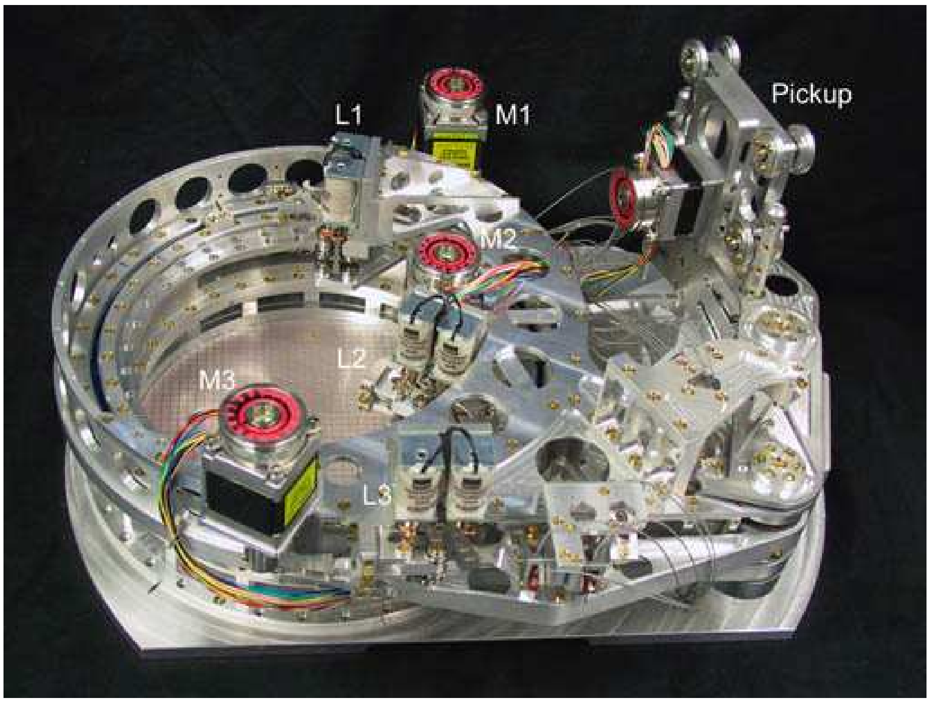

Fig. 5. Photograph of the cryogenic robot that places the fiber arms on the magnetic plate. The robot has three degrees of freedom with three cryogenic stepper motors (M1–3). The Pickup is coupled with a spider arm to be moved. Entire robot is locked by locking mechanisms (L1–3) when not in use. A rotation of the entire device and two linear movements along two sides of a parallelogram in principle allow placing the spider arms anywhere across the field of view, including rotation of the spider around the optical axis.

3.4 Overall Performance

The CROMOS described above excels in H-band and K-band sensitivity, speed (or integration time, or multiplex advantage, or sensitivity squared), and simultaneous wavelength coverage for detailed studies of faint sources with a spatial extent of 1–2". Because of its integral field nature, the device is also optimally suited for studying faint point sources. There are no slit losses and the source is always 'on' the detector. Figure 6 gives an impression of a typical application

(faint galaxy studies in the Chandra South area), along with a summary of its performance when compared to a long-slit spectrometer (ISAAC, NIRSPEC) and a warm multi-slit MOS (NIRMOS). In terms of overall speed, the proposed CROMOS is 3500 faster than ISAAC and NIRSPEC and about 60 times faster than NIRMOS.

The instrumental development described here is part of a combined effort of the Munich University Observatory and the Max-Planck Institut für extraterrestrische Physik. It derives its overall heritage from the SINFONI/SPIFFI and FORS developments for the VLT, and the LUCIFER development for the LBT.

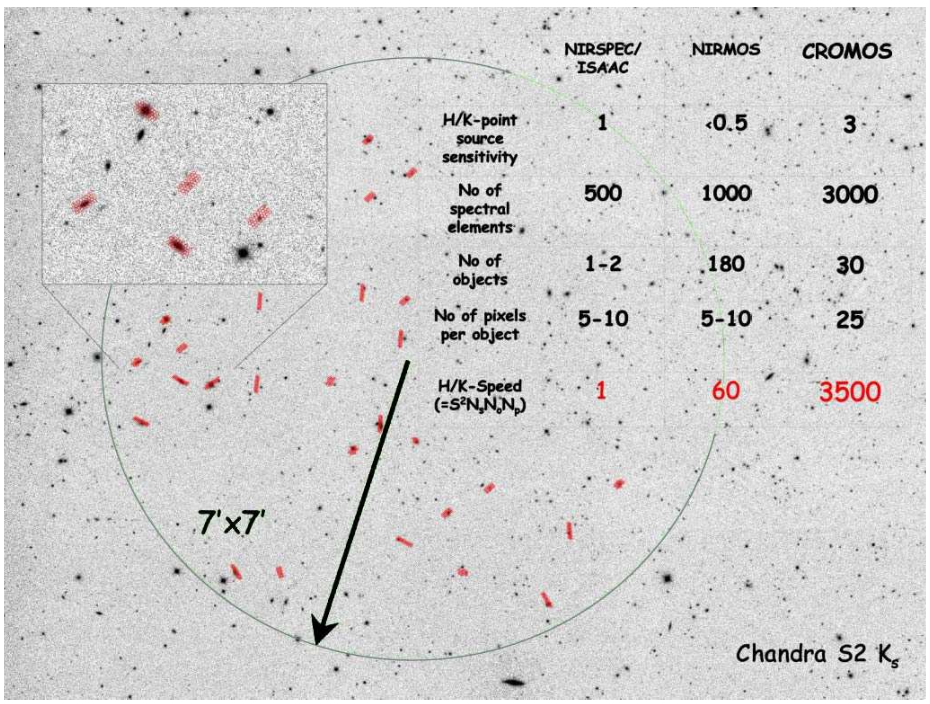

Fig. 6. ISAAC K_S image of the Chandra South (2) area, taken as part of the ESO EIS Deep survey, along with a mock lay-out of ∼30 IFUs from the proposed CROMOS. The table in the upper right is a comparison of the performance characteristics of the CROMOS, as compared to long slit spectrometers (ISAAC, NIRSPEC) and the warm, multi-slit NIRMOS instrument.

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